# Discrimination of the light CP-odd scalars between in the NMSSM and in the SLHM

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The presence of the light CP-odd scalar boson predicted in the next-to-minimal supersymmetric model (NMSSM) and the simplest little Higgs model (SLHM) dramatically changes the phenomenology of the Higgs sector. We suggest a practical strategy to discriminate the underlying model of the CP-odd scalar boson produced in the decay of the standard model-like Higgs boson. We define the decay rate of "the non $b$-tagged jet pair" with which we compute the ratio of decay rates into lepton and jets. They show much different behaviors between the NMSSM and the SLHM.



## INTRODUCTION

Discovery of Higgs bosons is the principal goal of the CERN Large Hadron Collider (LHC), which is essential for understanding the electroweak symmetry breaking. In the standard model (SM), there exists one scalar boson $h$ of which mass is constrained by a lower bound of 114 GeV from the direct search of $e^-e^+ \to Zh \to Zb\bar{b}$ process at CERN Large Electron Positron collider (LEP) [1]. At the LHC, the promising production channel is the gluon fusion, $pp \to gg \to h$. The Higgs boson dominantly decays into $WW/ZZ$ when $m_h > 140$ GeV, and into $b\bar{b}$ in the low mass region. Since $h \to b\bar{b}$ channel suffers from huge QCD background, the favored search channel is $h \to \gamma\gamma$. The LHC has reported that the accumulated data of this year exceeds 5 fb$^{-1}$ and more than 10 fb$^{-1}$ is expected in the next year [2]. If so, the SM-like Higgs boson might be observed at the early LHC era with the 7 TeV center-of-mass energy [3].

However, the ATLAS and the CMS group have examined the Higgs boson to obtain the null result in the region $m_h > 140$ GeV with data of 1 fb$^{-1}$ so far. There remains only the low mass window of 115 GeV$< m_H <$140 GeV, which will be narrowed soon with the data of 5 fb$^{-1}$ collected in 2011. As the LHC will run successfully to accumulate 15 fb$^{-1}$ next year, it is possible to exclude the whole region of $m_h < 600$ GeV instead of the observation of the Higgs signal. If the SM Higgs boson is excluded at the LHC, it is a clear evidence of the existence of the new physics beyond the SM. We have to deliberate the implication of the absence of the SM-like Higgs boson at this stage. In some scenarios of new physics models beyond the SM, it is hard to detect the SM-like Higgs boson, at least at the early stage of the LHC. One of the examples of this scenario is the next-to-minimal supersymmetric model (NMSSM) with an additional singlet superfield. In the NMSSM, the parameter space with a very light CP-odd scalar $a$ is allowed such that the SM-like CP-even Higgs boson can decay into a pair of light CP-odd scalar bosons with a large branching ratio [4]. Such a light CP-odd scalar sequentially decays into $b\bar{b}$, $c\bar{c}$, and $\tau^-\tau^+$ pairs depending on its mass. Then it would be much more difficult to identify the Higgs boson with four final states and we might miss the Higgs boson signal at the early LHC. Moreover in this case, other channels for Higgs boson decays are suppressed due to the large branching ratio of $h \to aa$. On the other hand, the present Higgs mass bound from the LEP data can be lowered due to the reduction of the $ZZh$ coupling and Br$(h \to b\bar{b})$ in this model [5]. The simplest little Higgs model (SLHM) with the $\mu$ parameter is another example of the model with the light CP-odd scalar [6]. The production and decays of the SM-like Higgs boson in the SLHM are similar to those in the NMSSM, such as the Higgs boson dominantly decays into a pair of light CP-odd scalars $\eta$ and the Higgs mass bound weakens [7–9].

In these scenarios, the promising channel to find the Higgs boson is $h \to aa/\eta\eta \to b\bar{b}b\bar{b}$ via $Wh$ and $Zh$ production at the LHC if $m_{a,\eta} > 2m_b$, which is feasible to observe the Higgs boson through this channel at the LHC with 14 TeV [8]. If $m_{a,\eta} < 2m_b$, it may be produced in radiative heavy quarkonium decays [10] or in associated production [11]. The collider signatures of the CP-odd scalar boson are similar at the LHC in both models, the NMSSM and the SLHM. Thus it is not easy to fix the underlying theory even if we observe a light CP-odd scalar boson at the LHC. Therefore it is very important to clarify the underlying structure of the light CP-odd scalar boson. In this Letter, we present a strategy to discriminate the underlying model of the CP-odd scalar boson assuming that the CP-odd scalar boson has been already discovered through $h \to aa/\eta\eta$ decays and its mass is measured. Since the producton cross

sections and the decay rates depend upon many model parameters as well as the final state masses, we cannot fix the model by the measured cross sections and branching ratios. If we accumulate enough number of CP-odd scalars to estimate the ratio of decay rates, however, the most parameter dependences are canceled and the features of the underlying models are revealed. Especially in the SLHM, the Yukawa couplings are commonly expressed by the new scale $f$ and $\tan\beta$ and the ratios of decay rates are determined by the $\eta$ mass and the final states masses only.

We consider the ratio of the decay rates into tau lepton pair to those into quark pairs. Since it is impossible to identify the $c$-jet and only partly possible to tag the $b$-jet, we define a new observable $\Gamma(j'j')$, the decay width into "non $b$-tagged jet pair", by subtracting tagged $b$-jet from the total jet decay rates. We show that it is possible to discriminate the underlying models of the CP-odd scalars with the ratio of the decay rates into tau lepton pair and into non $b$-tagged jet pair with an allowed value of the $b$-tagging efficiency. If we will not observe the SM-like Higgs boson at the early stage of the LHC, the light CP-odd scalar scenario should be concerned seriously. Then it will be very important to find out the underlying model of the CP-odd scalar.

## TWO SCENARIOS FOR THE LIGHT CP-ODD SCALAR FROM THE NMSSM AND THE SLHM

In the NMSSM, the Higgs sector is described by the superpotential [12],

$$W = \hat{Q}\hat{H}_u h_u \hat{U}^c + \hat{H}_d\hat{Q}h_d\hat{D}^c + \hat{H}_d\hat{L}h_e\hat{E}^c + \lambda\hat{S}(\hat{H}_u\hat{H}_d) + \frac{1}{3}\kappa\hat{S}^3, \tag{1}$$

where $\hat{S}$ is a singlet chiral superfield. The associated soft trilinear couplings are given by

$$V = \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + H.c.\ , \tag{2}$$

The effective $\mu$ term is generated by the vacuum expectation value (VEV) of the singlet scalar $s \equiv \langle\hat{S}\rangle$, yielding $\mu = \lambda s$. With an extra complex singlet scalar field, the Higgs sector of the NMSSM consists of three CP-even Higgs bosons, two CP-odd Higgs bosons, and a pair of charged Higgs boson and is described by six parameters $\lambda$, $\kappa$, $A_\lambda$, $A_\kappa$, $\tan\beta$, and $\mu_{\rm eff}$ where $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$. The relevant Lagrangian for CP-odd scalars is given by

$$\mathcal{L} = i\frac{g}{2m_W}p_{i1}\Big[m_d\tan\beta\ \bar{d}\gamma_5 d + m_u\cot\beta\ \bar{u}\gamma_5 u\Big]P_i\ , \tag{3}$$

where $\tan\beta = v_1/v_2$ and $p_{i1}$ are mixing matrix elements between pseudoscalar components $P_1$ and $P_2$ dropping the Goldstone mode. We introduce an angle $\gamma$ to represent the mixing such that

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \begin{pmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{pmatrix}\begin{pmatrix} a \\ A \end{pmatrix}\ , \tag{4}$$

where $a$ is the physical state of the light CP-odd scalar and $A$ that of the heavy one. We concentrate only on $a$ in this Letter.

The light CP-odd Higgs boson arises in the SLHM with the $\mu$ term, where the global symmetry is $[SU(3)\times U(1)_X]^2$ wiht the gauge symmetry $SU(3)\times U(1)_X$ as its diagonal subgroup. The symmetries are broken to the SM gauge symmetry by the VEV of the non-linear SU(3) triplet scalar fields, $\langle\mathbf{\Phi_{1,2}}\rangle = (0,0,f_{1,2})^T$. We assume that $f_{1,2}$ are of order TeV. The remnant degrees of freedom in the Goldstone boson sector are the $SU(2)_L$ doublet $H$ and a CP-odd scalar boson $\eta$. The Higgs potential is radiatively generated via fermion and gauge boson loops and so is the SM-like Higgs boson mass. However, the $\eta$ remains massless because it appears in the phase factor of $\mathbf{\Phi_{1,2}}$. The massless $\eta$ has a trouble with constraints from the rare $K$, $B$ decays, radiative $\Upsilon$ decays, and cosmology. Thus we introduce $-\mu^2(\mathbf{\Phi_1^\dagger\Phi_2} + H.c.)$ term to generate the mass term of CP-odd scalar, even though it breaks the global symmetry slightly. The fermion doublets of the SM are promoted to the $SU(3)$ triplets in this model. In addition, heavy fermions are required in order to cancel quadratic divergences of SM top quark and remove the anomaly of the gauge group. The relevant Lagrangian with Yukawa interactions is

$$\mathcal{L} = -i\sum_f \frac{m_f}{v}\ y_f^\eta\ \eta\ \bar{f}\gamma_5 f + \frac{m_t}{v}(i\eta\bar{T}P_R t + h.c)\ , \tag{5}$$

where the Yukawa couplings are

$$\begin{aligned} y_l^\eta &= y_{d,s,b}^\eta = -y_{u,c,t}^\eta = \frac{\sqrt{2}v}{f}\cot 2\beta, \\ y_Q^\eta &= -\frac{v}{f}[\cos 2\beta + \cos 2\theta_Q]\csc 2\beta\ , \end{aligned} \tag{6}$$

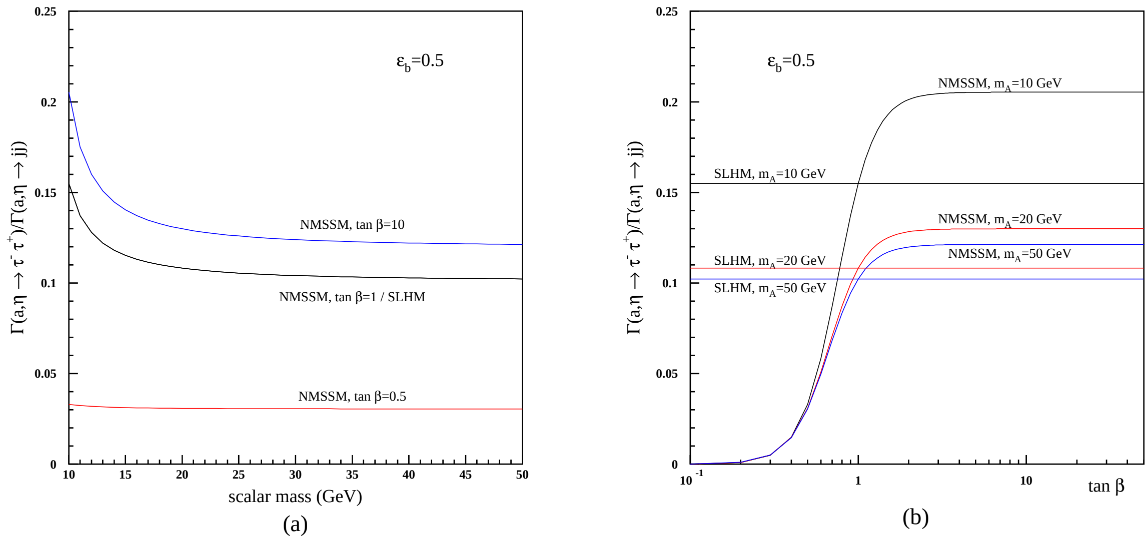


FIG. 1: The ratios of decay rates into $\tau^-\tau^+$ and into the non $b$-tagged two jet as functions of (a)the CP-odd scalar mass and (b) $\tan\beta$.

with leptons $l = e, \mu, \tau$, heavy quarks $Q = D, S, T$. In this model, the new physics scale $f^2 = f_1^2 + f_2^2$ and $\tan\beta = f_2/f_1$, and the mixing angles $\theta_{T,S,D}$ between the heavy quarks $T, S, D$ and SM quarks $t, s, d$ are defined by

$$\cos 2\theta_F = \sqrt{1 - \frac{2f^2}{v^2}\frac{m_q^2}{m_Q^2}\sin^2 2\beta}\ . \tag{7}$$

## DISCRIMINATORY SIGNATURES OF TWO LIGHT CP-ODD SCALARS

In our scenario, we assume that the light CP-odd scalar is produced by the SM-like Higgs boson decay, $h \to aa/\eta\eta$. Then the CP-odd scalar will decay into fermion pairs and gauge boson pairs, and the decay channels depend on its mass. The decays of $\eta$ in the SLHM are given in Ref. [9] and those of $a$ in the NMSSM given in Ref. [12]. Since the Yukawa couplings are proportional to the fermion masses, the dominant decay modes are $b\bar{b}$, $c\bar{c}$, and $\tau^-\tau^+$ when $m_{a,\eta} > 2m_b$. However, it is not likely to identify the $c$-quark jets at the LHC, we consider the decays into two jets instead. We define the "non $b$-tagged jet pair", $j'j'$, which is two jet event not tagged as $b$-quark jets. If we let the $b$-tagging efficiency as $\epsilon_b$, the decay rate of the non $b$-tagged two jet event is obtained by subtracting $b$-tagged events from total two jet events, *i.e.*

$$\Gamma(j'j') = \Gamma(b\bar{b})(1-\epsilon_b) + \Gamma(c\bar{c}) = \Gamma(jj) - \epsilon_b\Gamma(b\bar{b}), \tag{8}$$

where $\Gamma(jj)$ is the total decay width of the CP-odd scalar into two jets.

In the NMSSM, the decay width of $a$ to down type $f\bar{f}$ is given by,

$$\Gamma(a \to f\bar{f}) = \frac{N_C}{8\pi}\left(\frac{m_f}{v}\right)^2 C_\beta^2 \cos^2\gamma\ m_a \left(1 - \frac{4m_f^2}{m_a^2}\right)^{\frac{1}{2}}, \tag{9}$$

where $C_\beta = \tan\beta$ for down-type quarks and leptons, and $C_\beta = \cot\beta$ for up-type quarks.

If we consider the ratio of $b\bar{b}$ and $\tau^-\tau^+$, $\tan\beta$ dependence is canceled and the ratio is determined by only the final state masses and $m_a$, as is the case of the SLHM shown below. Thus we cannot discriminate two models. Instead we consider the ratio of $\tau^-\tau^+$ and non $b$-tagged two jet events, which reveals $\tan\beta$ dependence, as given by

$$\frac{\Gamma(a \to \tau^-\tau^+)}{\Gamma(a \to j'j')} = \frac{m_\tau^2 f(m_\tau)}{3m_b^2 f(m_b)(1-\epsilon_b) + 3m_c^2\cot^4\beta f(m_c)}, \tag{10}$$

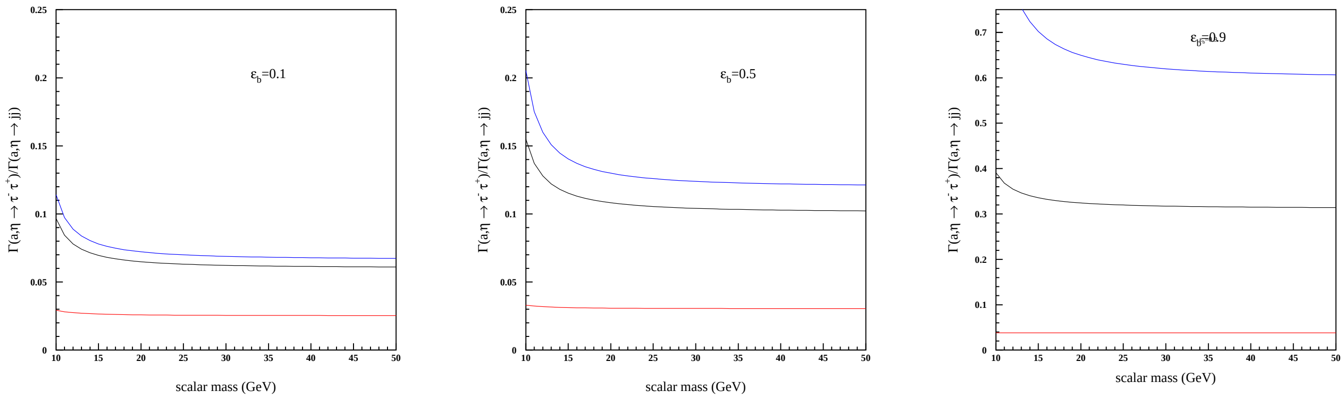


FIG. 2: The ratios of decay rates into $\tau^-\tau^+$ and into the non $b$-tagged two jet as functions of the CP-odd scalar mass with respect to the $b$-tagging efficiency, $\epsilon_b = 0.1, 0.5, 0.9$. The upper curve (blue) denote the NMSSM with $\tan\beta = 10$, the middle curves (black) the NMSSM with $\tan\beta = 1$ and the SLHM, and the lower curves (red) the NMSSM with $\tan\beta = 0.5$ in each plot.

where $f(m) = \sqrt{1 - 4m^2/m_a^2}$. We note that the additional parameter $\cos\gamma$ does not appear in the ratio of decay rates.

In the SLHM, the decay rates of $\eta$ into fermion pairs are given by

$$\Gamma(\eta \to f\bar{f}) = \frac{N_C}{8\pi}\left(\frac{m_f}{v}\right)^2 {y_f^\eta}^2 m_\eta \left(1 - \frac{4m_f^2}{m_\eta^2}\right)^{\frac{1}{2}} , \tag{11}$$

We now consider the ratios of their decay widths into fermions;

$$\frac{\Gamma(\eta \to f\bar{f})}{\Gamma(\eta \to f'\bar{f}')} = \frac{N_C\ m_f^2 \left(1 - 4m_f^2/m_\eta^2\right)^{\frac{1}{2}}}{N_C\ m_{f'}^2 \left(1 - 4m_{f'}^2/m_\eta^2\right)^{\frac{1}{2}}} . \tag{12}$$

Note that the ratio is determined by only the final state fermion masses and scalar mass and does not depend on any model parameters. Thus the ratio of the SLHM is identical to that of the NMSSM with $\tan\beta = 1$.

Figure 1 (a) depicts the ratios $\Gamma(a \to \tau^-\tau^+)/\Gamma(a \to j'j')$ as functions of $\tan\beta$ in the NMSSM and the SLHM. Note that the ratio of the SLHM falls on that of $\tan\beta = 1$ case in the NMSSM.

Figure 1 (b) depicts the $\tan\beta$ dependence of the ratio. If $\tan\beta > 1$, the $c\bar{c}$ contribution becomes less important and the ratio is saturated. The predictions for the SLHM do not depend on $\tan\beta$. Instead the SLHM plot crosses the NMSSM curves at $\tan\beta = 1$ for all $m_\eta$. Please note that the definitions of $\tan\beta$ in the NMSSM and the SLHM are different from each other.

We assume that we can observe an CP-odd scalar boson from the SM-like Higgs decay, and collect data enough for determination of branching ratios. If the origin of the CP-odd scalar is the SLHM, the ratio should be fixed, *e.g.* $\sim 0.11$ when $m_\eta > 20$ GeV. If we measured the ratio much different from that value, we can exclude the SLHM, and the NMSSM is a strong candidate. If $m_{a,\eta} \to 2m_b$, the kinematic factor for $b\bar{b}$ channel vanishes and the ratio is close to 1/3 due to the color factor.

In Fig. 1, we set $\epsilon_b = 0.5$. The $b$-tagging is achieved by several algorithms at the LHC, e.g. track counting, simple secondary vertex, and their variants. If we cannot tag $b$-jets, *i.e.* $\epsilon_b = 0$, the $b$-quark contribution dominates in the denominator and the $\tan\beta$ dependence of the ratio of Eq. (10) is very weak when $\tan\beta > 1$. Then it is hard to discriminate the NMSSM from the SLHM in this region. If $\epsilon_b = 1$, we can tag all $b$-jets, and we obtain the ratio $\Gamma(\tau\tau)/\Gamma(c\bar{c})$ to discriminate two models clearly, which it is an ideal case. We show the effects of the $b$-tagging efficiency on the $\tan\beta$ dependence of the ratio in Fig. 2. We can see that better the $b$-tagging, easier to discriminate the curves. The recent estimation of the CMS group tells us that the efficiency can reach 0.562 [14]. We find that it is conservatively possible to discriminate two models with the allowable valus of the$b$-tagging efficiency.

The $a/\eta \to \gamma\gamma$ channel might be useful to find the signal due to relatively low background [13]. However, the decay rates are too small to be measured $\sim 10^{-4}$, and even worse to involve many model parameters. Thus we do not consider this channel in this work.

## CONCLUDING REMARKS

The light CP-odd scalar boson with the dominant $h \to aa/\eta\eta$ decay provides a new phenomenology of the Higgs sector. We have to find the SM-like Higgs boson through identifying $a$ or $\eta$ owing to the large $\mathrm{Br}(h \to aa/\eta\eta)$. In this Letter, assuming that we have observed a CP-odd scalar boson, we present a strategy to determine it to be $a$ or $\eta$, the CP-odd scalar in the NMSSM or in the SLHM. The signal cross section and decay rates depend upon many undetermined parameters. Since the Yukawa couplings in the SLHM involve common dependence on model parameters, the ratios of the decay rates are expressed by final state masses and $m_a$. However, in the NMSSM, the Yukawa couplings for the up-type quarks involve $\cot\beta$, and those of down-type quarks and charged leptons involve $\tan\beta$ due to the supersymmetry. Therefore, the ratio of decay rates in the NMSSM can strongly depend on $\tan\beta$ and show much difference from that in the SLHM with fixed particle masses. We define the decay width of non $b$-tagged two jets events, where the $\tan\beta$ dependence remains in the practical reason. In conclusion, if we measure the ratio of decay rates into $\tau$ pair and non $b$-tagged two jets, we can easily discriminate two models in the case of $\tan\beta$ far from 1.

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